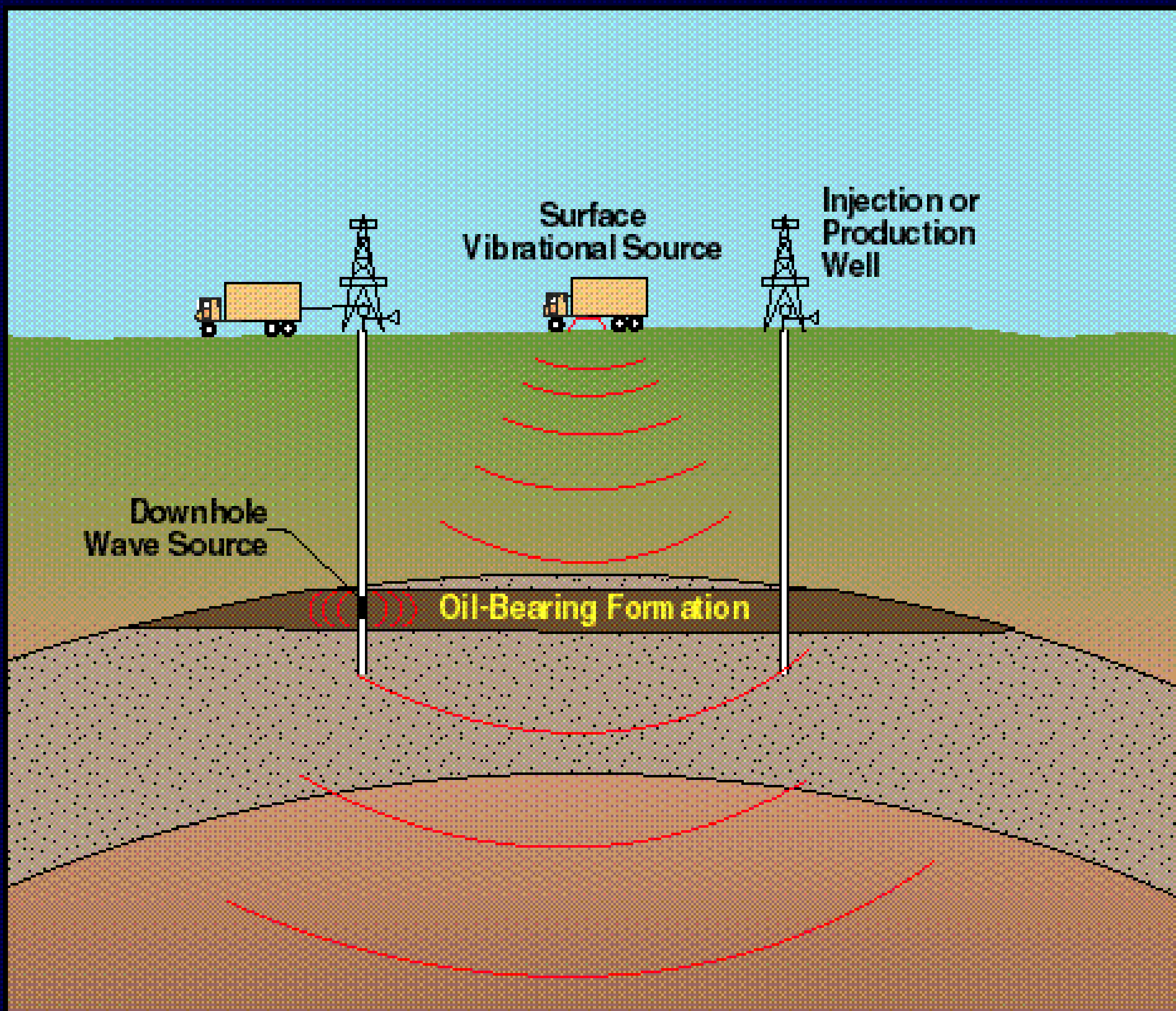
SEISMIC STIMULATION FOR ENHANCED PRODUCTION OF OIL RESERVOIRS



Downhole or surface seismic sources generate low-frequency (1 - 500 Hz) waves that interact with the reservoir formation and fluids to increase the oil production rate and/or total oil recovered.

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MEETING OBJECTIVES

- Review status and plans for DOE research
- Update (voluntary) on industry activities
- Define major problems and unknowns
- Identify short and long term project goals
- Define roles of LANL, LBNL and industry
- Project administrative issues
  - -procedure for new companies joining
  - -propose industry representative(s)

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SEISMIC STIMULATION FOR ENHANCED PRODUCTION OF OIL RESERVOIRS

Current Industry Participants:

Chevron, Conoco, Fluidic Technologies, Halliburton, Marathon Oil, Oil and Gas Consultants Intl. PerfClean Intl., Phillips Petroleum, Piezo Sona-Tool, Reservoir Stimulation Technology, Texaco, Wave Energy Resources

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DOE Participants:

Los Alamos National Laboratory
Lawrence Berkeley National Laboratory

SEISMIC STIMULATION FOR ENHANCED PRODUCTION OF OIL RESERVOIRS

Background:

- Roughly 60% of domestic oil remains unproduced.
- Seismic waves can increase oil production.
- 50% or more increase in recovery is possible.
- Field tests give widely varying results.
- Laboratory data are inconclusive.
- Stimulation mechanisms are poorly understood.
- More basic R&D needed to increase field success.

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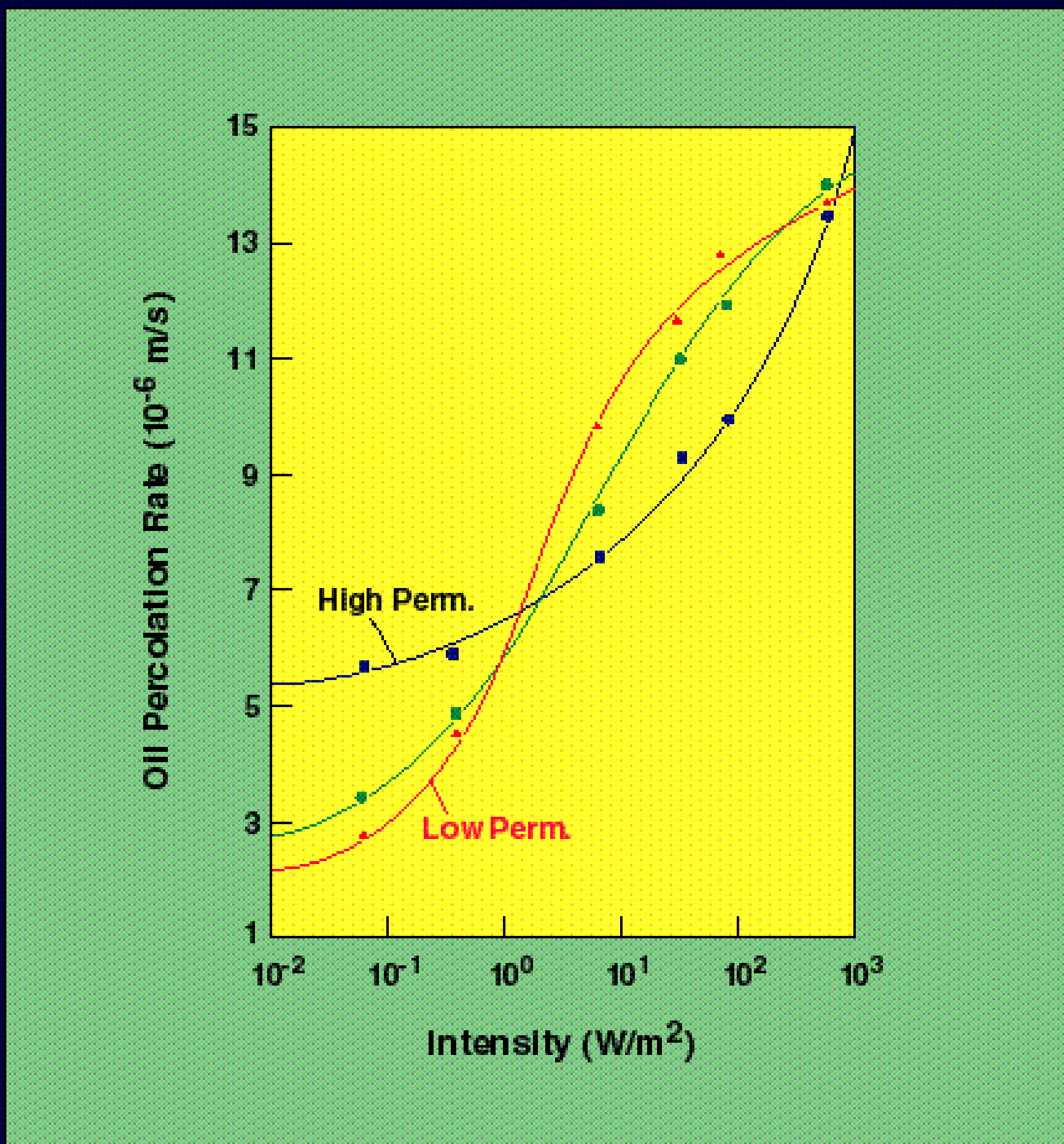
Ashiepkov (1989)

Oil percolation rates through sandstone versus applied acoustic intensity at 30 - 400 Hz for 3 initial sample permeabilities.



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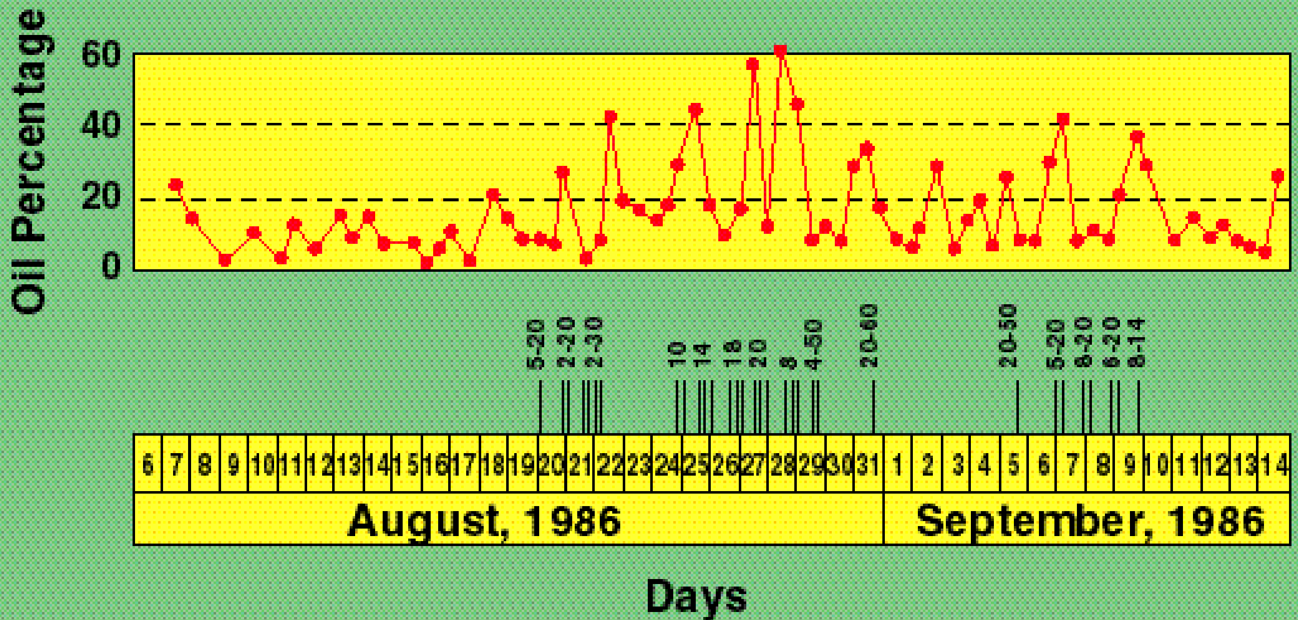
Kissin (1991)

Effects of 20-ton Vibroseis stimulation on the oil percentage of produced fluid from a depleted reservoir in the Northern Caucasus. Reservoir was 1200 m deep and 10 m thick.



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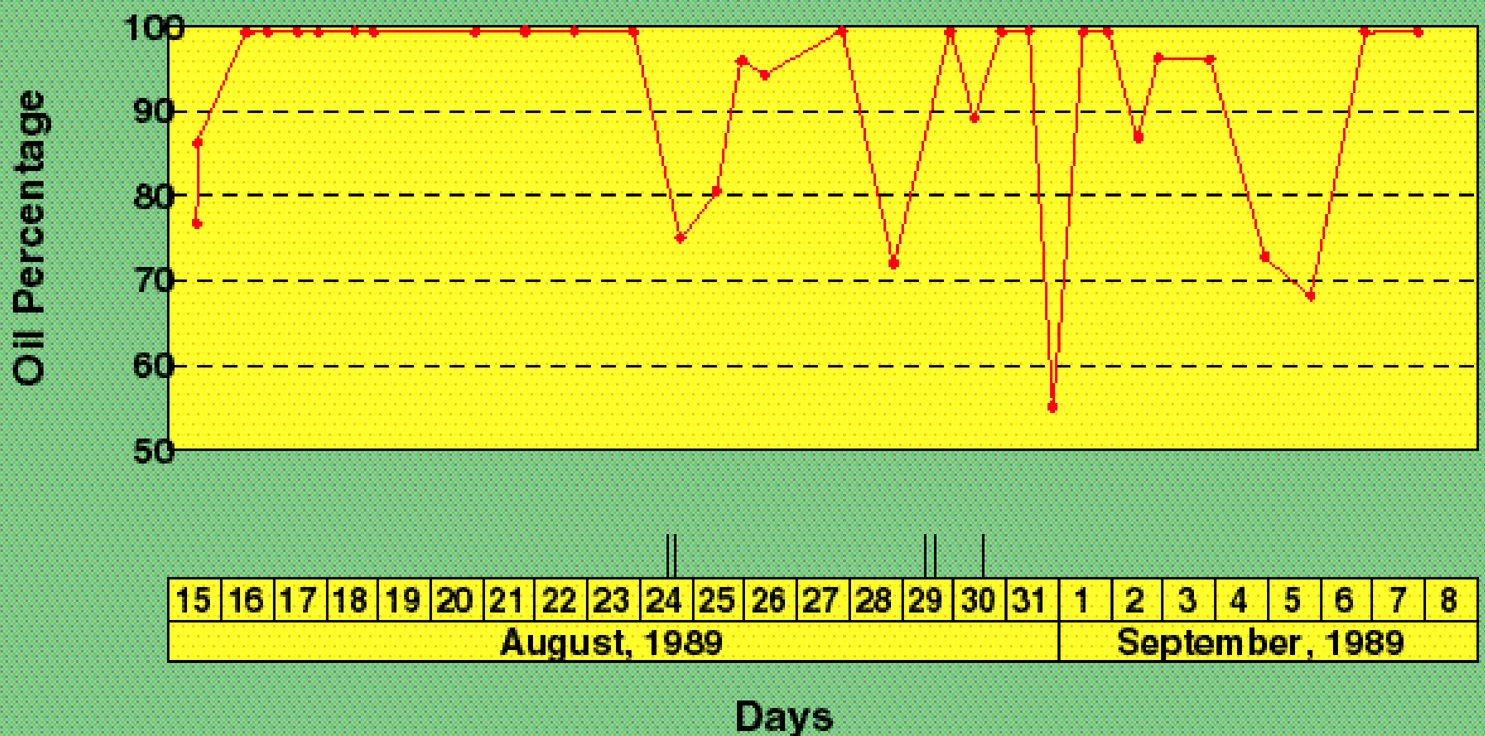
Nikolaev & Kuznetsov (1990)

Effects of 20-ton Vibroseis stimulation on the oil percentage of produced fluid from a productive reservoir. Initial oil cut was close to 100%. Stimulation was applied at approximately 20 Hz.



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Possible Mechanisms of Enhanced Oil Production

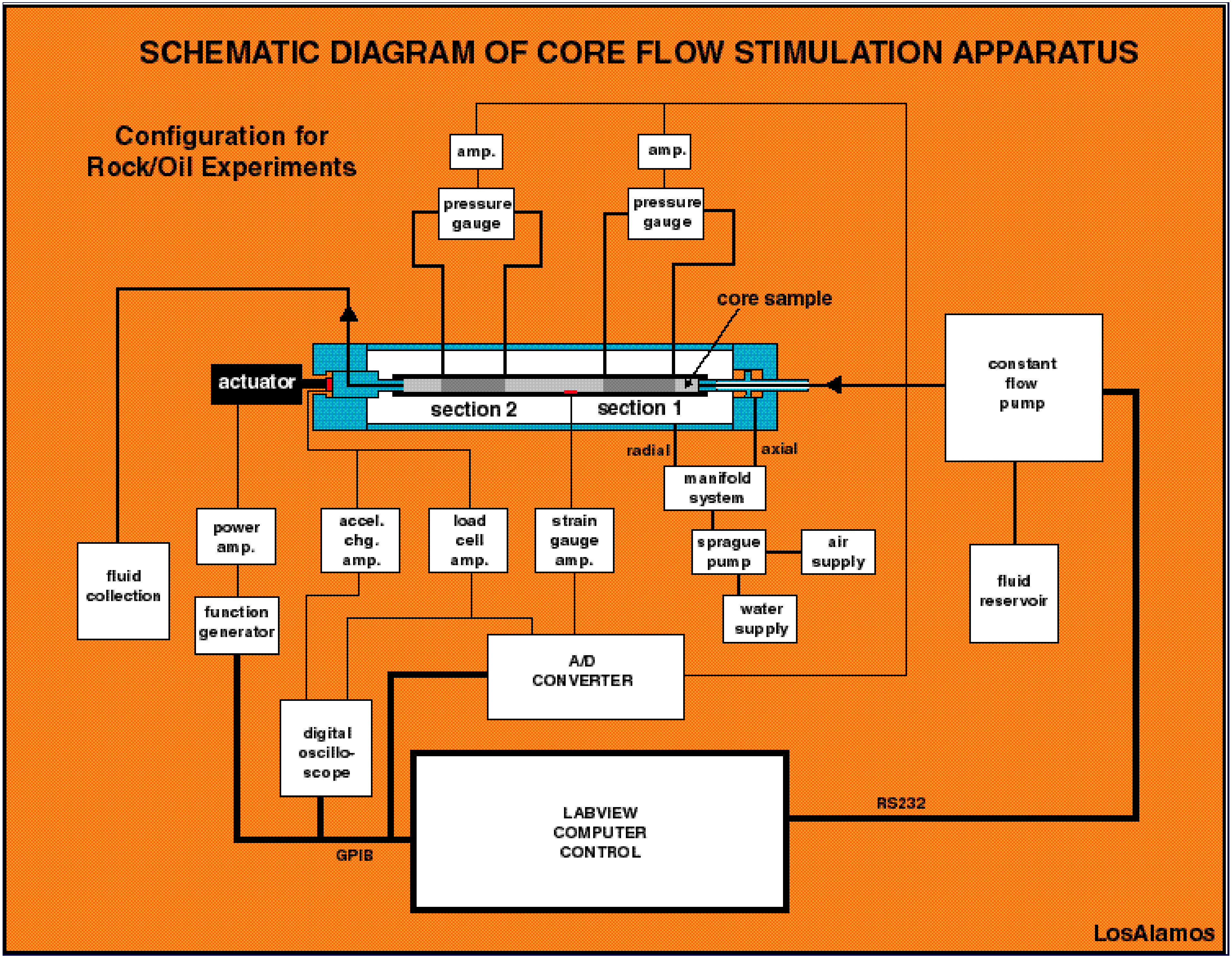
Low-Frequency Stress Waves May:

- increase absolute permeability by destroying pore wall boundary films or liberating in-situ fines
- reduce residual oil saturation by coalescence of dispersed oil droplets
- mobilize oil trapped in low-permeability zones inaccessible to water floods
- increase relative permeability of oil during 2-phase oil/water flow

SEISMIC STIMULATION FOR ENHANCED PRODUCTION OF OIL RESERVOIRS

Research Focus Areas:

- Laboratory core flow experiments.
- Numerical and theoretical modeling.
- Field experimental testing.


SCHEMATIC DIAGRAM OF CORE FLOW STIMULATION APPARATUS
Configuration for
Rock/Oil Experiments
amp.
amp.
pressure
gauge
pressure
gauge
core sample
actuator
section 2
section 1
constant
flow
pump
radial
axial
manifold
system
power
amp.
accel.
chg.
amp.
load
cell
amp.
strain
gauge
amp.
sprague
pump
air
supply
fluid
collection
function
generator
water
supply
fluid
reservoir
A/D
CONVERTER
digital
oscillo-
scope
LABVIEW
COMPUTER
CONTROL
RS232
GPIB
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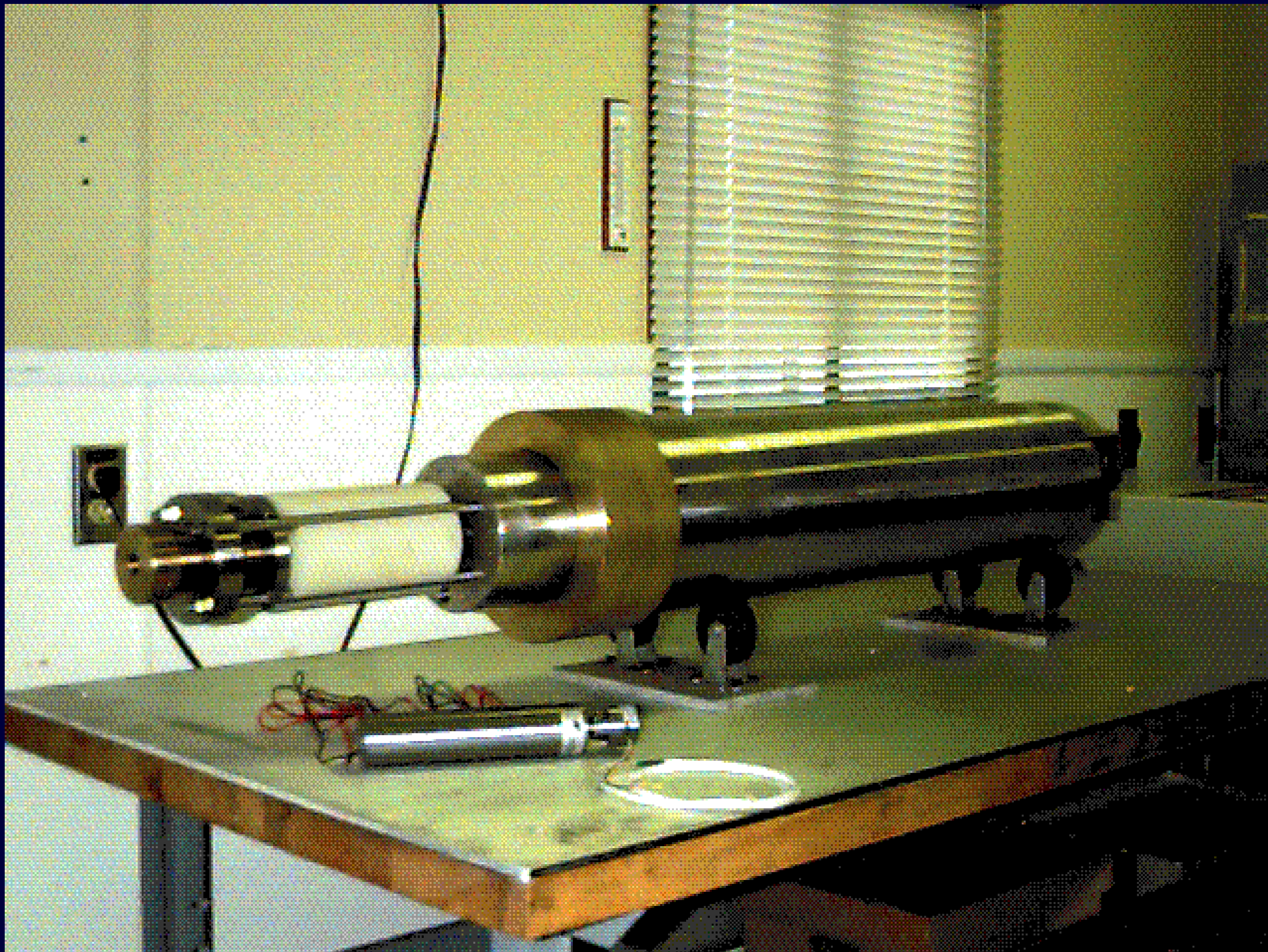

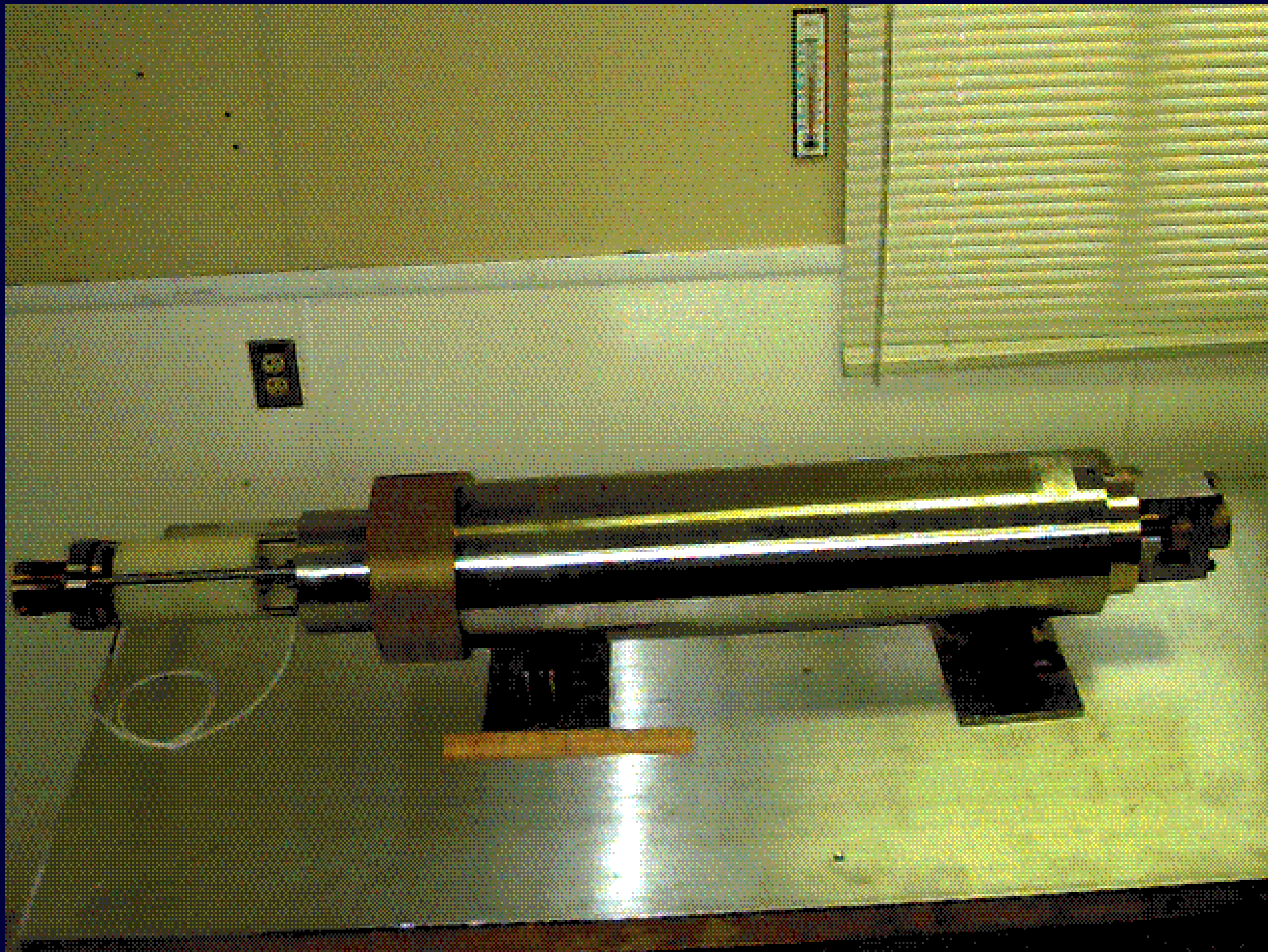

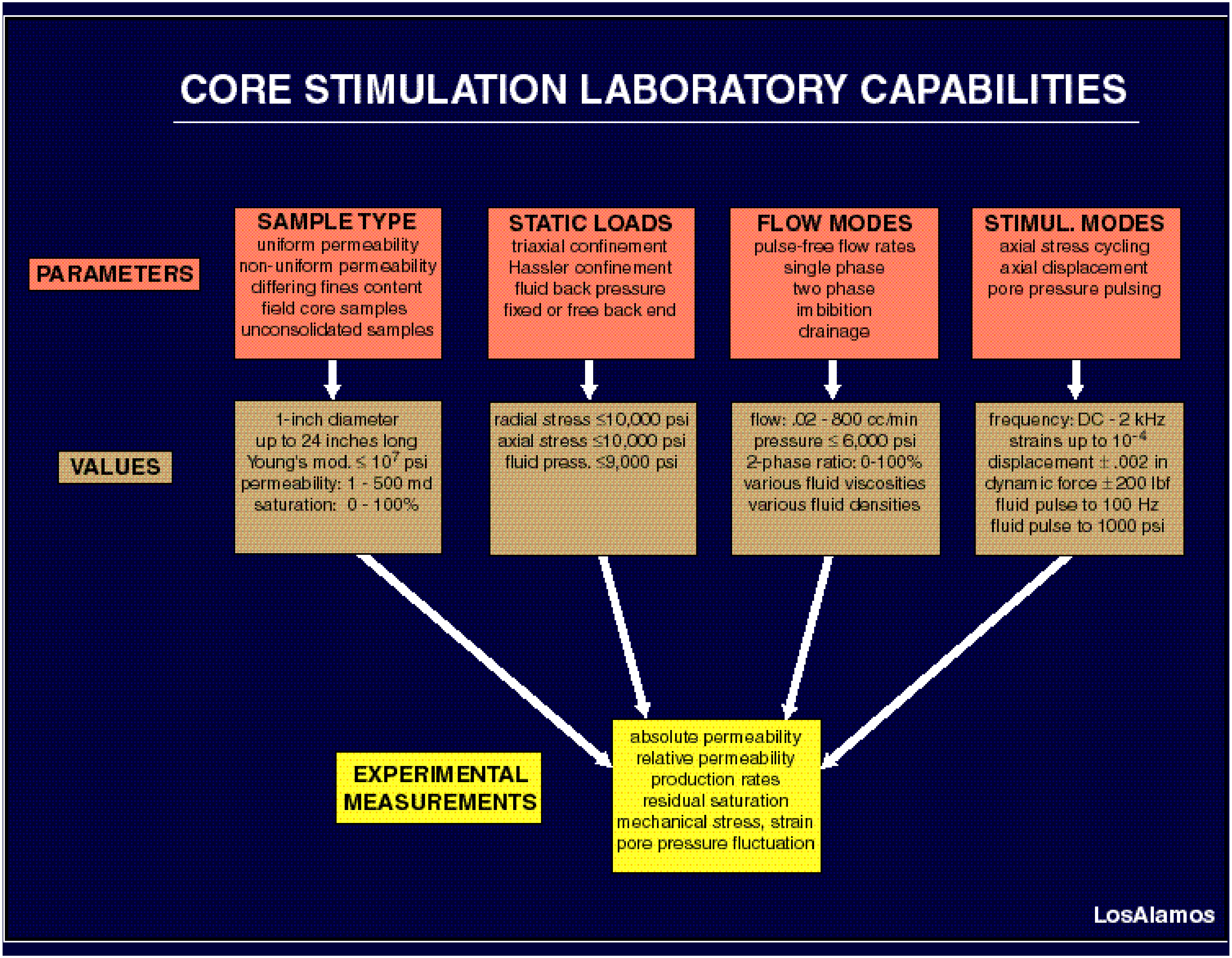
CORE STIMULATION LABORATORY CAPABILITIES
PARAMETERS
SAMPLE TYPE
uniform permeability
non-uniform permeability
differing fines content
field core samples
unconsolidated samples
STATIC LOADS
triaxial confinement
Hassler confinement
fluid back pressure
fixed or free back end
FLOW MODES
pulse-free flow rates
single phase
two phase
imbibition
drainage
STIMUL. MODES
axial stress cycling
axial displacement
pore pressure pulsing
VALUES
1-inch diameter
up to 24 inches long
Young's mod. ≤ 10^7 psi
permeability: 1 - 500 md
saturation: 0 - 100%
radial stress ≤10,000 psi
axial stress ≤10,000 psi
fluid press. ≤9,000 psi
flow: .02 - 800 cc/min
pressure ≤ 6,000 psi
2-phase ratio: 0-100%
various fluid viscosities
various fluid densities
frequency: DC - 2 kHz
strains up to 10^{-4}
displacement ± .002 in
dynamic force ± 200 lbf
fluid pulse to 100 Hz
fluid pulse to 1000 psi
EXPERIMENTAL MEASUREMENTS
absolute permeability
relative permeability
production rates
residual saturation
mechanical stress, strain
pore pressure fluctuation
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LAB EXPERIMENTS PLANNED FOR FY98

SAMPLES:

- Berea Sandstone
- Fontainbleau Sandstone
- Carbonate Rocks
- Diatomite
- Unconsolidated Sand
- Synthetic Cores

EFFECTS:

- Absolute Perm.
- Relative Perm.
- Production Rate
- Residual Saturation
- Fluid Mobilization
- Wave Parameters

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CORE FLOW STIMULATION EXPERIMENTS PERFORMED

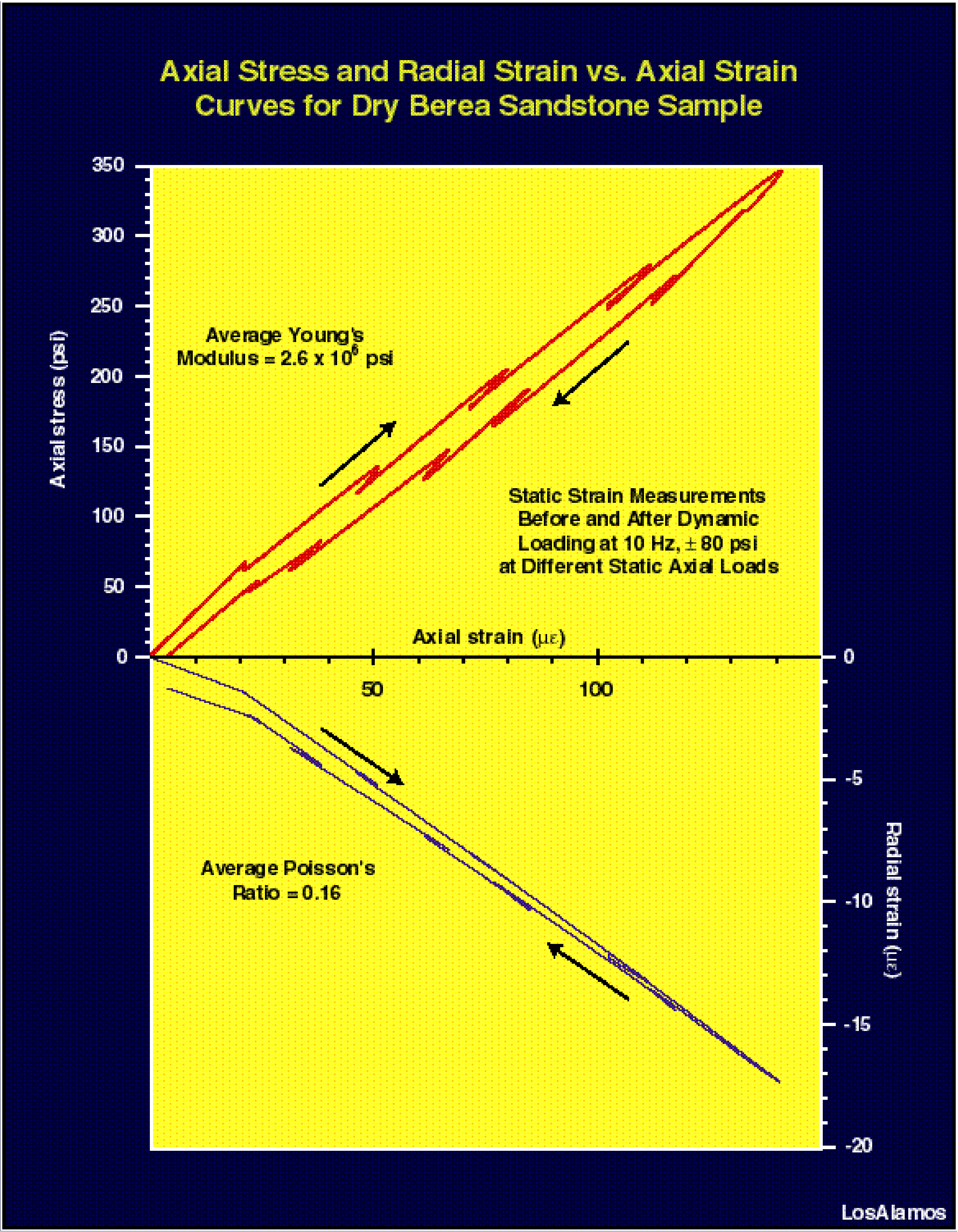
- Absolute permeability enhancement (2 Berea and 1 sand sample)
- Reduction of residual decane saturation after drainage and imbibition
- Mobilization of trapped DNAPL in a sand core during water flood
- Reduction of permeability damage caused by fines migration in Berea

BEREA SANDSTONE SAMPLE PHYSICAL AND ELASTIC PROPERTIES

- Diameter: 0.98 in (2.5 cm)
- Length: 12.56 in (31.9 cm)
- Cross-Section Area: 0.751 in^2 (4.8 cm^2)
- Total Volume: 155 mL
- Connected Pore Volume: 38 mL
- Connected Porosity: 0.24
- Nominal Permeability: 500 md
- Saturated Density: 149 lb/ft^3 (2390 kg/m^3)
- Acoustic Velocity: 7900 ft/s (2400 m/s)
- Young's Modulus: 2.6×10^6 psi (18 GPa)
- Poisson's Ration: 0.16

TYPICAL STIMULATION PARAMETERS USED FOR BEREA EXPERIMENTS

- Frequency Range: 50 - 100 Hz
- Axial Load: $\pm$ 60 lbf (267 N)
- Axial Stress: $\pm$ 80 psi (0.5 MPa)
- Axial Strain: $\pm$ 60 $\mu\varepsilon$
- Axial Displacement: $\pm$ 0.001" (20 μm)
- Axial Acceleration: $\pm$ 0.2 g (2 m/s^2)
- Pore Pressure: << 0.3 psi (2 kPa)
- Acoustic Intensity: 0.1 W/m^2


Axial Stress and Radial Strain vs. Axial Strain Curves for Dry Berea Sandstone Sample
Axial stress (psi)
350
300
250
200
150
100
50
0
Average Young's Modulus = 2.6 x 10^6 psi
Static Strain Measurements Before and After Dynamic Loading at 10 Hz, ± 80 psi at Different Static Axial Loads
Axial strain (με)
50
100
Average Poisson's Ratio = 0.16
Radial strain (με)
0
-5
-10
-15
-20
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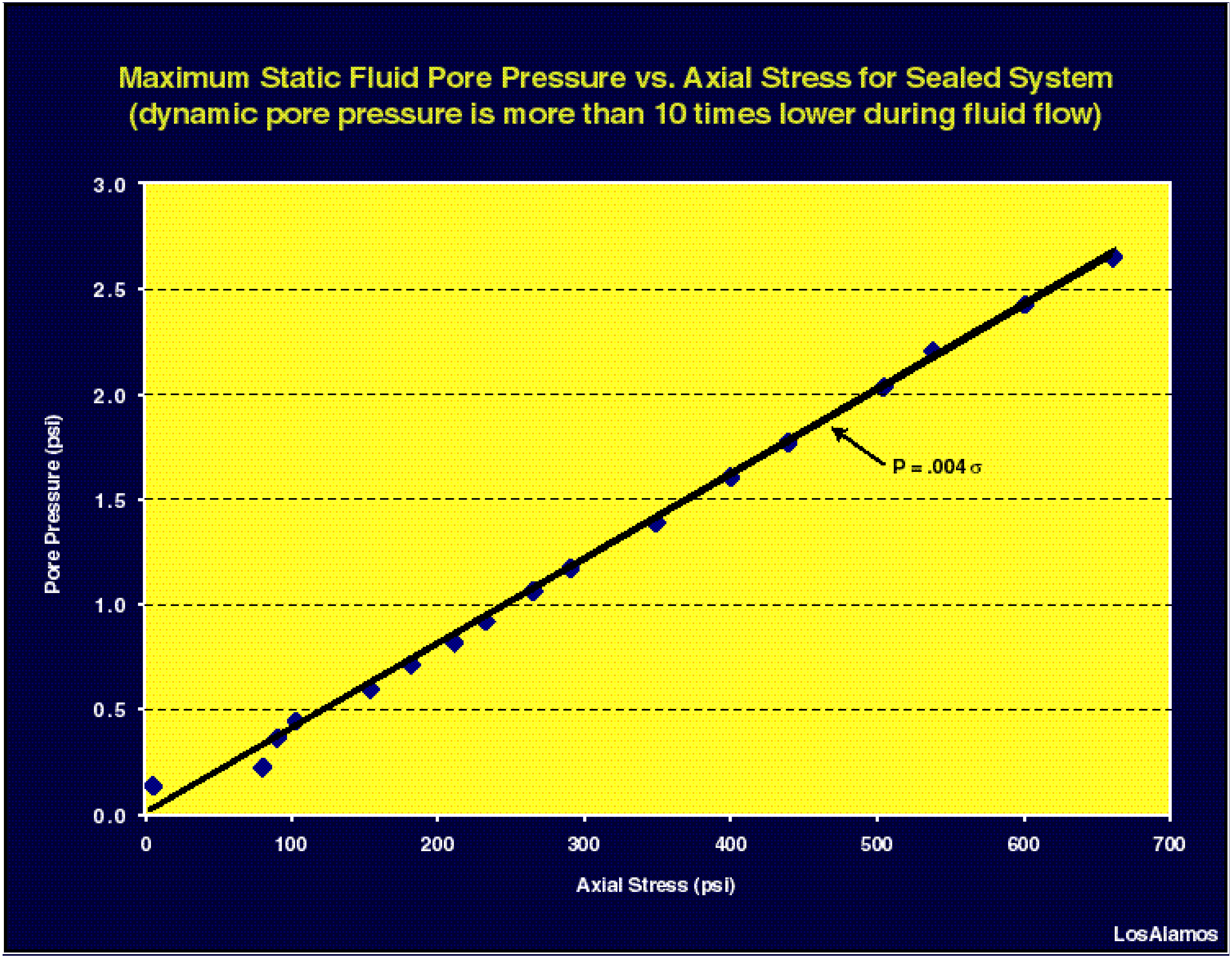
Maximum Static Fluid Pore Pressure vs. Axial Stress for Sealed System
(dynamic pore pressure is more than 10 times lower during fluid flow)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Pore Pressure (psi)
0
100
200
300
400
500
600
700
Axial Stress (psi)
P = .004 σ
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BEREA PERMEABILITY AND FINES EXPERIMENTAL PROCEDURE

- Confine core at 1000 psi radial and 800 psi axial
- Evacuate sample and saturate with brine
- Start brine flow and measure initial permeability
- Stimulate and measure permeability changes
- Liberate clay fines by briefly flowing fresh water
- Resume brine flow and measure permeability drop
- Stimulate to mobilize fines and restore permeability
- Change flow rate and direction during stimulation

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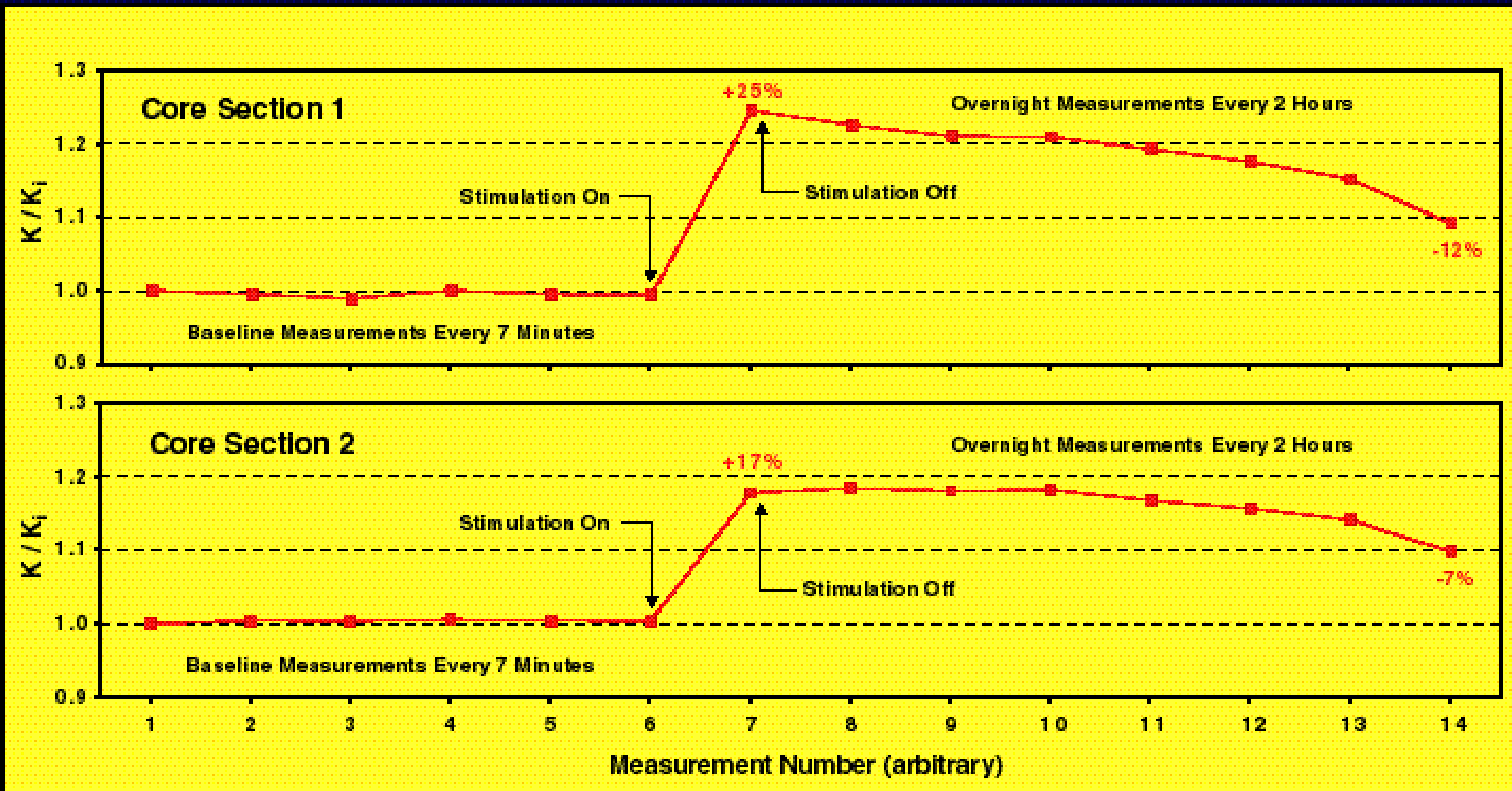
Permeability Changes Observed in 2 Core Sections Before, During and After 10 Minutes Continuous Stimulation at 50 Hz Frequency and ± 80 psi Axial Stress



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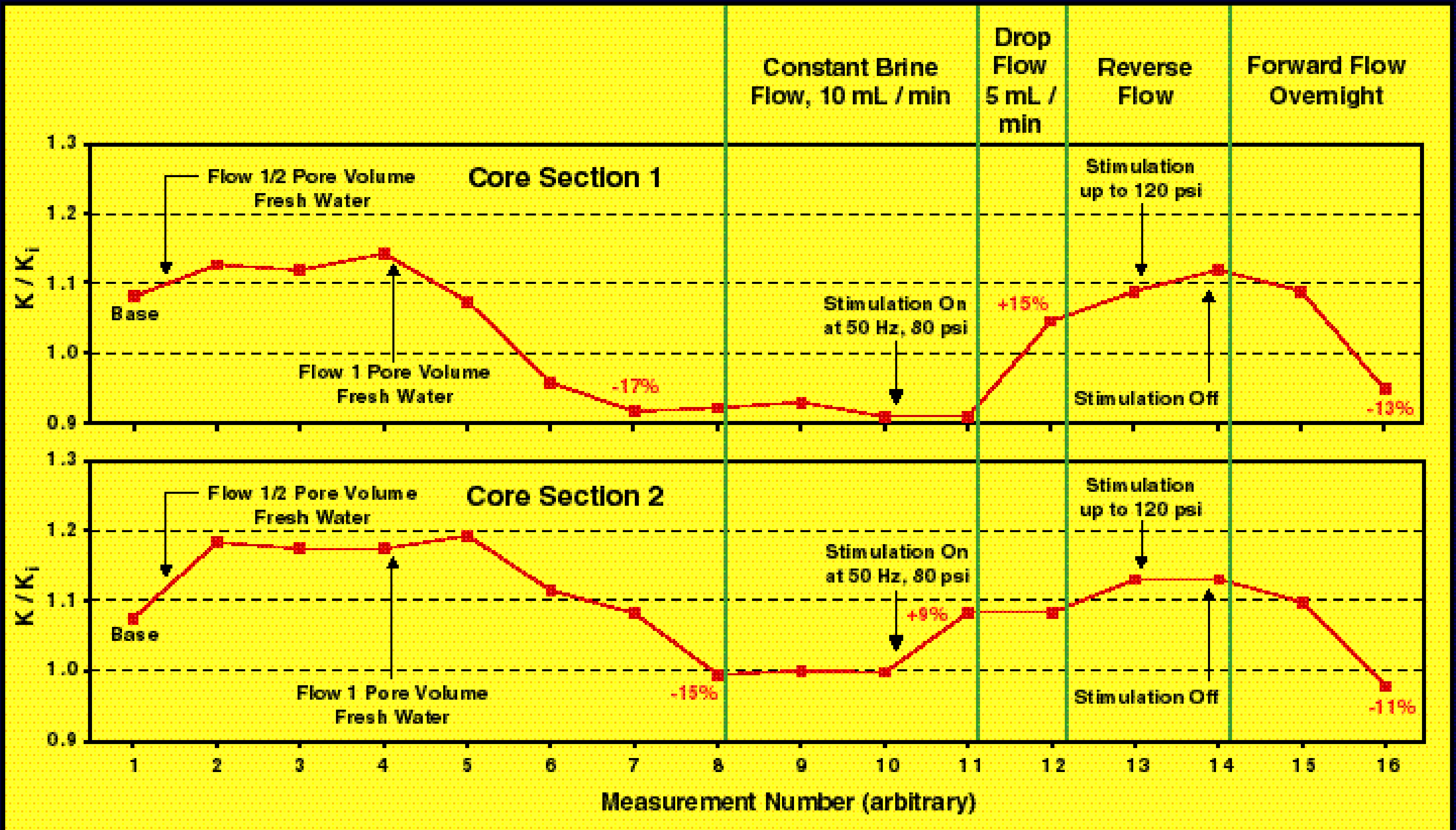
Permeability Changes Caused by Fresh-Water Fines Mobilization Followed by Stress Stimulation during Forward and Reverse Brine Flow



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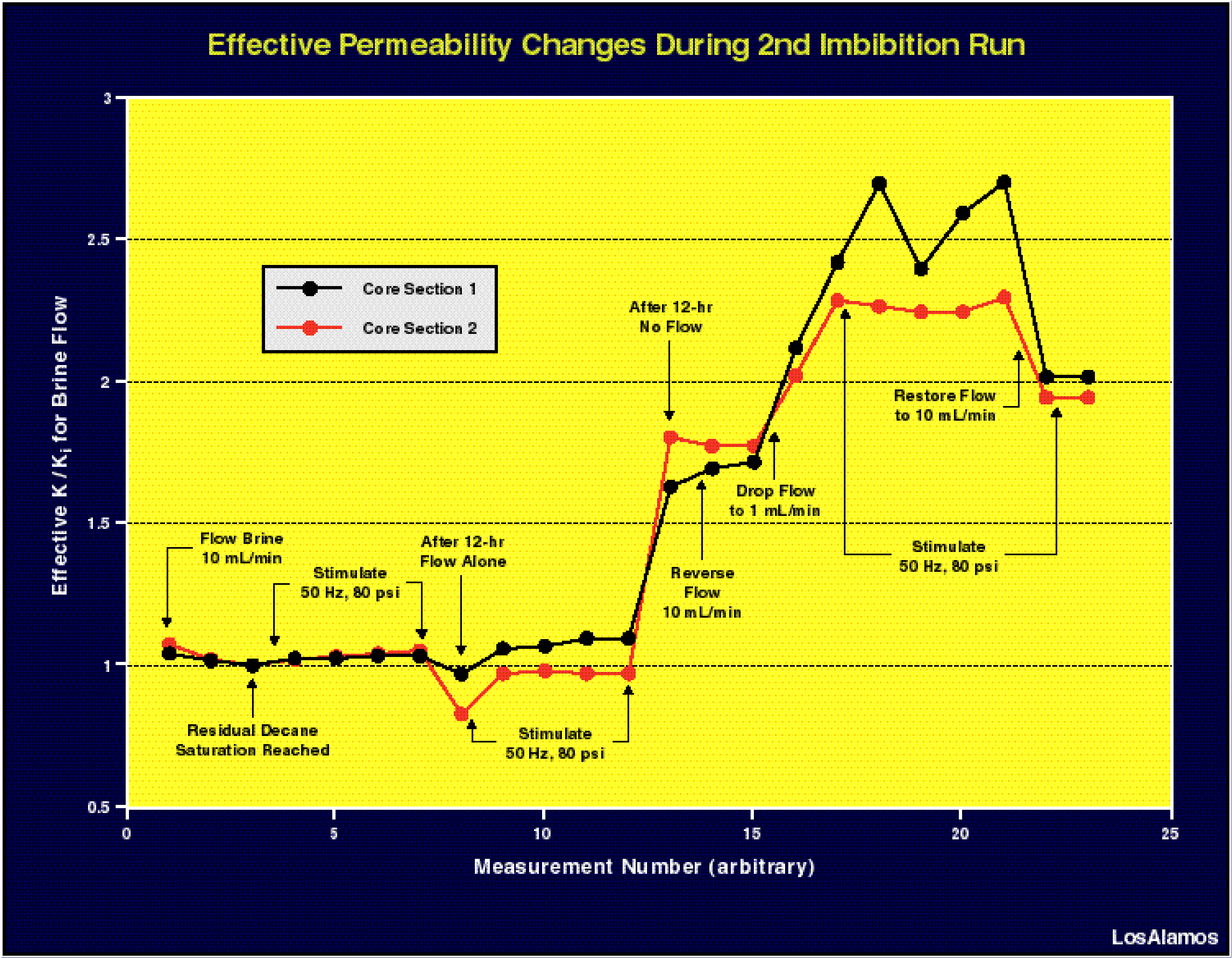
DECANE-BRINE DRAINAGE / IMBIBITION EXPERIMENTAL PROCEDURE

- Start with core initially brine saturated
- Drainage with decane until no more brine produced
- Stimulate to try decreasing S_{RW}
- Imbibition with brine until no more decane produced
- Stimulate to try decreasing S_{RO}
- Repeat drainage / imbibition cycle
- Change flow rate and direction during stimulation
- Measure effective permeability changes

DECANE-BRINE DRAINAGE / IMBIBITION SATURATION AND PERMEABILITY HISTORY

flow operation	core fluid content after each run				effective perm. (md) to flowing phase	
	brine		decane			
	mL	%P.V.	mL	%P.V.	section 1	section 2
brine sat.	37.8	100	0	0	689	789
drainage	9.5	25	28.3	75	638 - 678	617 - 698
imbibition	27.0	71	10.8	29	104 - 226	126 - 257
drainage	9.8	26	28.0	74	593 - 650	801 - 812
imbibition	26.2	69	11.6	31	90 - 185	99 - 228



Effective Permeability Changes During 2nd Imbibition Run
Core Section 1
Core Section 2
Effective K / K$_i$ for Brine Flow
Measurement Number (arbitrary)
0.5
1
1.5
2
2.5
3
0
5
10
15
20
25
Flow Brine 10 mL/min
Stimulate 50 Hz, 80 psi
After 12-hr Flow Alone
Residual Decane Saturation Reached
Stimulate 50 Hz, 80 psi
After 12-hr No Flow
Reverse Flow 10 mL/min
Drop Flow to 1 mL/min
Stimulate 50 Hz, 80 psi
Restore Flow to 10 mL/min
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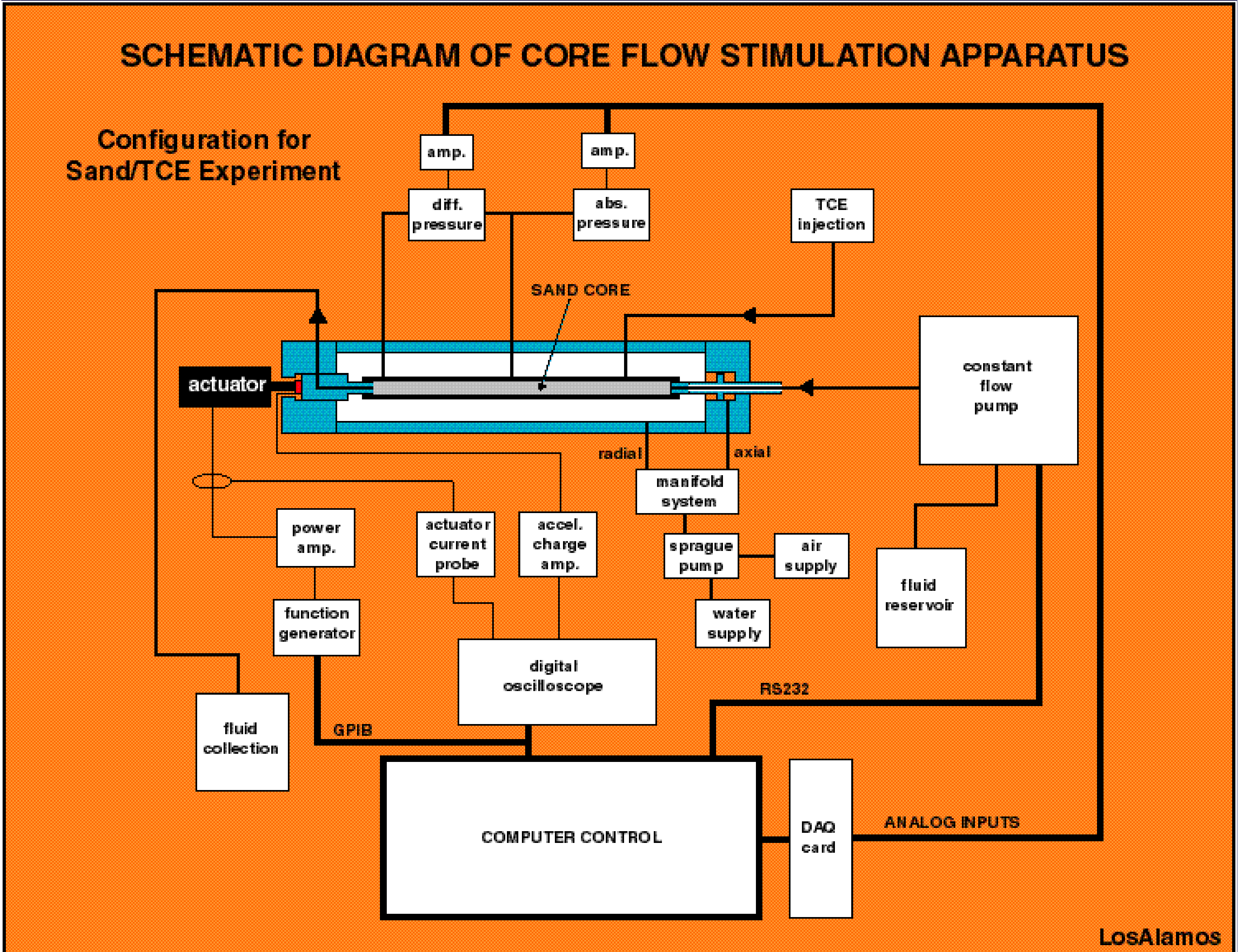

SCHEMATIC DIAGRAM OF CORE FLOW STIMULATION APPARATUS
Configuration for
Sand/TCE Experiment
amp.
amp.
diff. pressure
abs. pressure
TCE injection
SAND CORE
actuator
constant flow pump
radial
axial
manifold system
power amp.
actuator current probe
accel. charge amp.
sprague pump
air supply
water supply
fluid reservoir
function generator
digital oscilloscope
fluid collection
RS232
GPIB
COMPUTER CONTROL
DAQ card
ANALOG INPUTS
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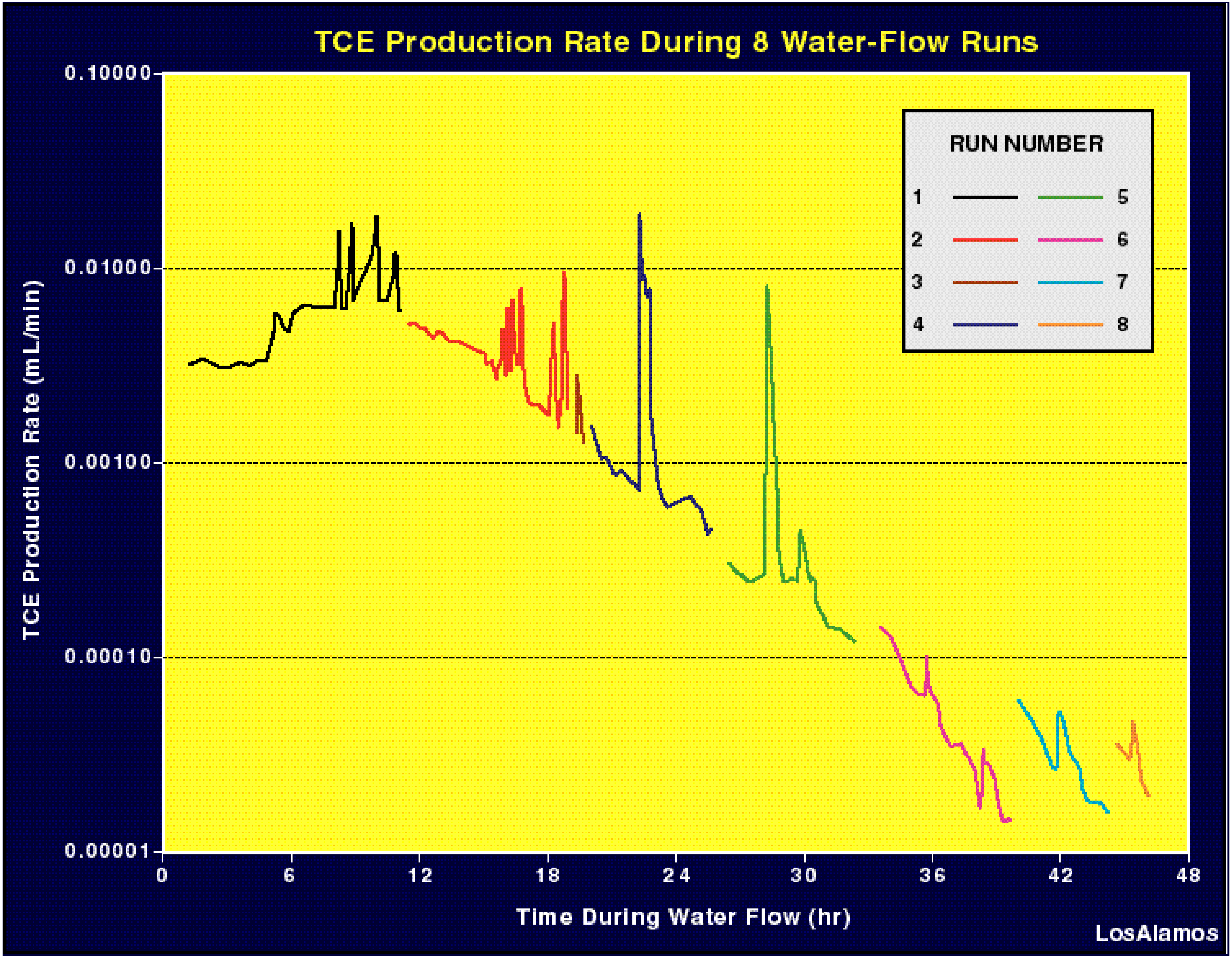
TCE PRODUCTION ENHANCEMENT EXPERIMENTAL PROCEDURE

- Pack sand into sleeve and apply confinement
- Evacuate sample and saturate with water
- Inject 10% pore volume of TCE into sand
- Initiate pulse-free flow of water through sand
- Measure effluent TCE concentration with GC
- Stimulate and measure TCE production change
- Measure applied displacement and pressure


TCE Production Rate During 8 Water-Flow Runs
RUN NUMBER
1
2
3
4
5
6
7
8
0.10000
0.01000
0.00100
0.00010
0.00001
TCE Production Rate (mL/min)
0
6
12
18
24
30
36
42
48
Time During Water Flow (hr)
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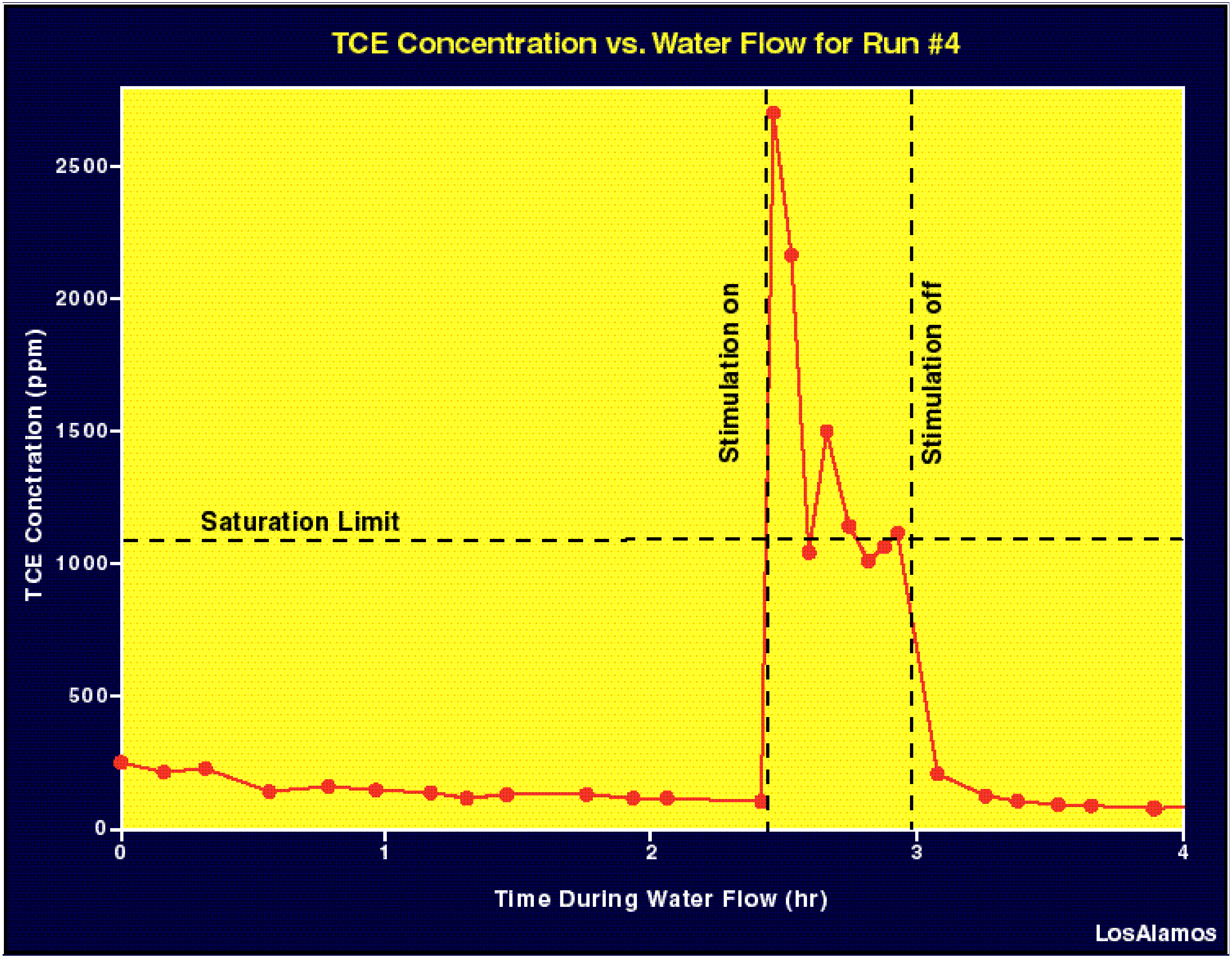
TCE Concentration vs. Water Flow for Run #4
TCE Conctration (ppm)
2500
2000
1500
1000
500
0
Time During Water Flow (hr)
0
1
2
3
4
Saturation Limit
Stimulation on
Stimulation off
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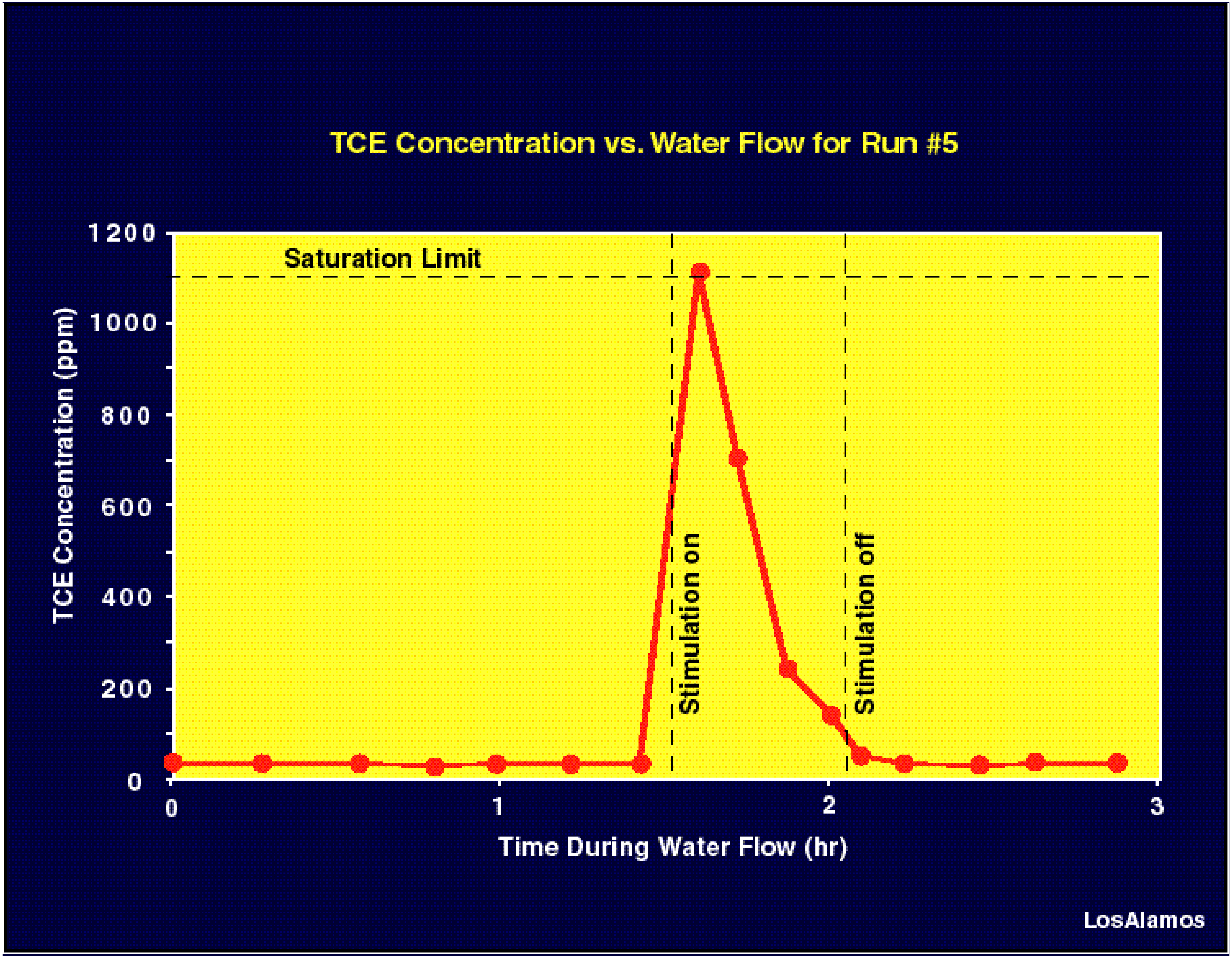
TCE Concentration vs. Water Flow for Run #5
Saturation Limit
Stimulation on
Stimulation off
TCE Concentration (ppm)
1200
1000
800
600
400
200
0
0
1
2
3
Time During Water Flow (hr)
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